It's Time to Replace TCP in the Datacenter

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This position paper has been updated since its original publication in October of 2022 in order to correct errors and add clarification. Updates are in italics; none of the original text has been modified. The paper has triggered discussion and dissent; for pointers to comments on the paper, see the Homa Wiki: https://homa-transport.atlassian.net/wiki/spaces/HOMA/overview#replaceTcp.

Abstract

In spite of its long and successful history, TCP is a poor transport protocol for modern datacenters. Every significant element of TCP, from its stream orientation to its expectation of in-order packet delivery, is wrong for the datacenter. It is time to recognize that TCP's problems are too fundamental and interrelated to be fixed; the only way to harness the full performance potential of modern networks is to introduce a new transport protocol into the datacenter. Homa demonstrates that it is possible to create a transport protocol that avoids all of TCP's problems. Although Homa is not APIcompatible with TCP, it should be possible to bring it into widespread usage by integrating it with RPC frameworks.

1 Introduction

The TCP transport protocol [9] has proven to be phenomenally successful and adaptable. At the time of TCP's design in the late 1970's, there were only about 100 hosts attached to the existing ARPANET, and network links had speeds of tens of kilobits/second. Over the decades since then, the Internet has grown to billions of hosts and link speeds of 100 Gbit/second or more are commonplace, yet TCP continues to serve as the workhorse transport protocol for almost all applications. It is an extraordinary engineering achievement to have designed a mechanism that could survive such radical changes in underlying technology.

However, datacenter computing creates unprecedented challenges for TCP. The datacenter environment, with millions of cores in close proximity and individual applications harnessing thousands of machines that interact on microsecond timescales, could not have been envisioned by the designers of TCP, and TCP does not perform well in this environment. TCP is still the protocol of choice for most datacenter applications, but it introduces overheads on many levels, which limit application-level performance. For example, it is well-known that TCP suffers from high tail latency for short messages under mixed workloads [2]. TCP is a major contributor to the "datacenter tax" [3, 12], a collection of low-level overheads that consume a significant fraction of all processor cycles in datacenters.

This position paper argues that TCP's challenges in the datacenter are insurmountable. Section 3 discusses each of the major design decisions in TCP and demonstrates that every one of them is wrong for the datacenter, with significant negative consequences. Some of these problems have been discussed in the past, but it is instructive to see them all together in one place. TCP's problems impact systems at multiple levels, including the network, kernel software, and applications. One example is load balancing, which is essential in datacenters in order to process high loads concurrently. Load balancing did not exist at the time TCP was designed, and TCP interferes with load balancing both in the network and in software.

Section 4 argues that TCP cannot be fixed in an evolutionary fashion; there are too many problems and too many interlocking design decisions. Instead, we must find a way to introduce a radically different transport protocol into the datacenter. Section 5 discusses what a good transport protocol for datacenters should look like, using Homa [19, 21] as an example. Homa was designed in a clean-slate fashion to meet the needs of datacenter computing, and virtually every one of its major design decisions was made differently than for TCP. As a result, some problems, such as congestion in the network core fabric, are eliminated entirely. Other problems, such as congestion control and load balancing, become much easier to address. Homa demonstrates that it is possible to solve all of TCP's problems.

Complete replacement of TCP is unlikely anytime soon, due to its deeply entrenched status, but TCP can be displaced for many applications by integrating Homa into a small number of existing RPC frameworks such as gRPC [6]. With this approach, Homa's incompatible API will be visible only to framework developers and applications should be able to switch to Homa relatively easily.

2 Requirements

Before discussing the problems with TCP, let us first review the challenges that must be addressed by any transport protocol for datacenters.

Reliable delivery. The protocol must deliver data reliably from one host to another, in spite of transient failures in the

network.

Low latency. Modern networking hardware enables roundtrip times of a few microseconds for short messages. The transport protocol must not add significantly to this latency, so that applications experience latencies close to the hardware limit. The transport protocol must also support low latency at the tail, even under relatively high network loads with a mix of traffic. Tail latency is particularly challenging for transport protocols; nonetheless, it should be possible to achieve tail latencies for short messages within a factor of 2–3x of the best-case latency [19].

High throughput. The transport protocol must support high throughput in two different ways. Traditionally, the term "throughput" has referred to *data throughput*: delivering large amounts of data in a single message or stream. This kind of throughput is still important. In addition, datacenter applications require high *message throughput*: the ability to send large numbers of small messages quickly for communication patterns such as broadcast and shuffle [15]. Message throughput has historically not received much attention, but it is essential in datacenters.

In order to meet the above requirements, the transport protocol must also deal with the following problems:

Congestion control. In order to provide low latency, the transport protocol must limit the buildup of packets in network queues. Packet queuing can potentially occur both at the edge (the links connecting hosts to top-of-rack switches) and in the network core; each of these forms of congestion creates distinct problems.

Efficient load balancing across server cores. For more than a decade, network speeds have been increasing rapidly while processor clock rates have remained nearly constant. Thus it is no longer possible for a single core to keep up with a single network link; both incoming and outgoing load must be distributed across multiple cores. This is true at multiple levels. At the application level, high-throughput services must run on many cores and divide their work among the cores. At the transport layer, a single core cannot keep up with a high speed link, especially with short messages. Load balancing impacts transport protocols in two ways. First, it can introduce overheads (e.g. the use of multiple cores causes additional cache misses for coherence). Second, load balancing can lead to hot spots, where load is unevenly distributed across cores; this is a form of congestion at the software level. Load balancing overheads are now one of the primary sources of tail latency [21], and they are impacted by the design of the transport protocol.

NIC offload. There is increasing evidence that software-based transport protocols no longer make sense; they simply cannot provide high performance at an acceptable cost. For example:

• The best software protocol implementations have endto-end latency more than 3x as high as implementations where applications communicate directly with the NIC via kernel bypass.

- Software implementations give up a factor of 5–10x in small message throughput, compared with NICoffloaded implementations.
- Driving a 100 Gbps network at 80% utilization in both directions consumes 10–20 cores just in the networking stack [16, 21]. This is not a cost-effective use of resources.

Thus, in the future, transport protocols will need to move to special-purpose NIC hardware. The transport protocol must not have features that preclude hardware implementation. Note that NIC-based transports will not eliminate software load balancing as an issue: even if the transport is in hardware, application software will still be spread across multiple cores.

3 Everything about TCP is wrong

This section discusses five key properties of TCP, which cover almost all of its design:

- · Stream orientation
- Connection orientation
- Bandwidth sharing ("fair" scheduling)
- Sender-driven congestion control
- In-order packet delivery

Each of these properties represents the wrong decision for a datacenter transport, and each of these decisions has serious negative consequences.

3.1 Stream orientation

The data model for TCP is a stream of bytes. However, this is not the right data model for most datacenter applications. Datacenter applications typically exchange discrete *messages* to implement remote procedure calls. When messages are serialized in a TCP stream, TCP has no knowledge about message boundaries. This means that when an application reads from a stream, there is no guarantee that it will receive a complete message; it could receive less than a full message, or parts of several messages. TCP-based applications must mark message boundaries when they serialize messages (e.g., by prefixing each message with its length), and they must use this information to reassemble messages on receipt. This introduces extra complexity and overheads, such as maintaining state for partially-received messages.

The streaming model is disastrous for software load balancing. Consider an application that uses a collection of threads to serve requests arriving across a collection of streams. Ideally, all of the threads would wait for incoming messages on any of the streams, with messages distributed across the threads. However, with a byte stream model there is no guarantee that a read operation returns an entire message. If multiple threads both read from a stream, it is possible that parts of a single message might be received by different threads. In principle it might be possible for the threads to coordinate and reassemble the entire message in one of the threads, but this is too expensive to be practical.

Instead, TCP applications must use one of two inferior forms of load balancing, in which each stream is owned by a

single thread. The first approach, used by memcached [17], is to divide a collection of streams statically among the threads, where each thread handles all of the requests arriving on its streams. This approach is prone to hot spots, where one thread receives a disproportionate share of incoming requests. The second approach, used in RAMCloud [22], dedicates one thread to read all incoming messages from all streams and then dispatch messages to other threads for service. This allows much better load balancing across worker threads, but the dispatcher thread becomes a throughput bottleneck. Furthermore, the need for each request to pass through two separate threads adds significant software overhead and increases latency. Thus, the dispatcher thread approach is effective only if request service times are relatively long.

The fundamental problem with streaming is that the units in which data is received (ranges of bytes) do not correspond to dispatchable units of work (messages). There is no point in waking up a thread to receive part of a message; it will not be able to process the message until it receives the entire message. And, if a thread receives multiple messages in a single read operation, it can only process one of them at a time; it would be better for each message to be dispatched to a different thread so the messages can be processed concurrently.

Streaming's negative impact on load balancing will carry over into a future world where transport processing is offloaded to the NIC. In this world, the NIC should perform load balancing, dispatching incoming requests across a collection of application threads via kernel bypass. However, this will not be possible, since information about message boundaries is application-specific and unknown to the transport layer. Applications will still have to use one of the approaches described above, each of which impacts latency and/or throughput.

Streaming has an additional impact on tail latency because it induces head-of-line blocking. Messages sent on a single stream must be received in order; this means that a short message can be delayed behind a long message in the same stream. We observed this phenomenon in RAMCloud, where small time-sensitive replication requests from one server to another could be delayed by long background requests for log compaction, resulting in a 50x increase in write latency [22].

Finally, the reliability guarantees provided by streaming are not the right ones for applications. Applications want *round trip* guarantees. A client application wants an assurance that its request will be delivered and processed, and that it will receive a response; if any of these fails, the client would like an error notification. However, a stream guarantees only best-effort delivery of data in one direction. The client will receive no notification if the server does not send a response, and under some conditions there will be no notification if the server machine crashes. As a result, clients must implement their own end-to-end timeout mechanisms, even though TCP already has timers of its own. These mechanisms introduce additional overheads.

3.2 Connection orientation

TCP requires long-lived connection state for each peer that an application communicates with. Connections are undesirable in datacenter environments because applications can have hundreds or thousands of them, resulting in high overheads in space and/or time. For example, the Linux kernel keeps about 2000 bytes of state for each TCP socket, excluding packet buffers; additional state is required at application level.

Facebook found the memory demands for a separate connection between each application thread and each server "prohibitively expensive" [20]. To reduce these overheads, application threads communicate through a collection of proxy threads that manage connections to all the servers. This allows a single connection for each server to be shared across all the application threads on that host, but it adds overhead for communicating through the proxies. To reduce the proxy overheads, Facebook uses UDP instead of TCP for requests that can tolerate UDP's unreliability, but this sacrifices congestion control.

The overheads for connection state are also problematic when offloading the transport to the NIC, due to limited resources on the NIC chip. This problem is well known in the Infiniband community [5, 10, 11]. For many years, RDMA NICs could cache the state for only a few hundred connections; if the number of active connections exceeded the cache size, information had to be shuffled between host memory and the NIC, with a considerable loss in performance.

Another problem with connections is that they require a setup phase before any data can be transmitted. In TCP the setup phase has a nontrivial cost, since it requires an additional round-trip between the hosts. Traditionally, connections have been long-lived, so the setup cost can be amortized across a large number of requests. However, in new serverless environments applications have very short lifetimes, so it is harder to amortize the cost of connection setup.

It seems to be an article of faith in the networking community that connections are required in order to achieve desirable properties such as reliable delivery and congestion control, but connections carry a high cost and Section 5 will show that it is possible to achieve these properties without connections.

3.3 Bandwidth sharing

In TCP, when a host's link is overloaded (either for incoming or outgoing traffic), TCP attempts to share the available bandwidth equally among the active connections. This approach is also referred to as "fair scheduling".

Unfortunately, scheduling disciplines like this are well known to perform poorly under load. When receiving several large messages, bandwidth sharing causes all of them to finish slowly. Run-to-completion approaches such as SRPT (Shortest Remaining Processing Time) provide better overall response time because they dedicate all of the available resources to a single task at a time, ensuring that it finishes quickly. It is difficult implement run-to-completion with TCP

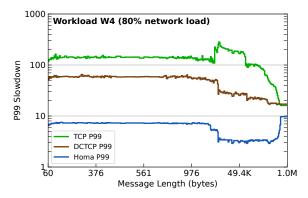


Figure 1: 99th percentile slowdown as a function of message length for Linux kernel implementations of TCP, DCTCP, and Homa, running on a 40-node CloudLab cluster with 25 Gbps network links running at 80% average utilization (see [21] for details). The workload is based on a message size distribution measured on a Hadoop cluster at Facebook. Slowdown is the round-trip trip time for a message on a loaded cluster, divided by the time for Homa messages of the same length in an unloaded system.

because TCP has no information about message boundaries; thus, it does not know when a task is "complete".

Furthermore, in spite of the name "fair scheduling", TCP's approach discriminates heavily against short messages. Figure 1 shows how round-trip latencies for messages of different sizes slow down when running on a heavily loaded network, compared to messages of the same size on an unloaded network. With TCP, short messages suffer a slowdown almost 10x worse than the longest messages. DCTCP reduces the gap somewhat, but short messages still suffer 3x worse treatment than long ones. Short message latency is critical in datacenter environments, so this discrimination is problematic.

3.4 Sender-driven congestion control

TCP drives congestion control from senders, which voluntarily slow their rate of packet transmission when they detect congestion. Senders have no first-hand knowledge of congestion, which can happen either in the core fabric or at edge links between top-of-rack switches and receivers, so they rely on congestion signals related to buffer occupancy. In the worst case, switch queues overflow and packets are dropped, leading to timeouts. More commonly, switches generate ECN notifications when queue lengths reach a certain threshold [25], or senders detect increases in round-trip times due to queueing [18, 13]; some newer approaches use programmable switches to generate more precise information such as exact queue lengths [14, 1]. Senders then use this information to back off on packet transmission.

Congestion control in TCP is hobbled by two limitations. First, congestion can only be detected when there is buffer occupancy; this virtually guarantees some packet queueing when the network is loaded. Second, TCP does not take advantage of the priority queues in modern network switches. Thus, all packets are treated equally and queues generated by long messages (where throughput matters more than latency) will cause delays for short messages.

These limitations lead to a "pick your poison" dilemma where it is difficult to simultaneously optimize both latency and throughput. The only way to ensure low latency for short messages is to keep queue lengths near zero in the network. However, this risks buffer under-runs, where links are idle even though there is traffic that could use them; this reduces throughput for long messages. The only way to keep links fully utilized in the face of traffic fluctuations is to allow buffers to accumulate in the steady state, but this causes delays for short messages.

Furthermore, it takes about 1 RTT for a sender to find out about traffic changes, so senders must make decisions based on out-of-date information. As messages get shorter and networks get faster, more and more messages will complete in less than 1 RTT, which makes the information received by senders less and less reliable.

Congestion control has been studied extensively, both for TCP and for other streaming approaches such as RDMA. These efforts have resulted in considerable improvements, but it is unlikely that the latency vs. throughput dilemma can be completely resolved without breaking some of TCP's fundamental assumptions.

3.5 In-order packet delivery

TCP assumes that packets will arrive at a receiver in the same order they were transmitted by the sender, and it assumes that out-of-order arrivals indicate packet drops. This severely restricts load balancing, leading to hot spots in both hardware and software, and consequently high tail latency.

In datacenter networks, the most effective way to perform load balancing is to perform *packet spraying*, where each packet is independently routed through the switching fabric to balance loads on links. However, packet spraying cannot be used with TCP since it could change the order in which packets arrive at their destination. Instead, TCP networks must use *flow-consistent routing*, where all of the packets from a given connection follow the same path through the network fabric. Flow-consistent routing ensures in-order packet delivery, but it virtually guarantees that there will be overloaded links in the network core, even when the overall network load is low. All that is needed for congestion is for two large flows to hash to the same intermediate link; this hot spot will persist for the life of the flows and cause delays for any other messages that also pass over the affected link.

I hypothesize that flow-consistent routing is responsible for virtually all of the congestion that occurs in the core of datacenter networks.

In-order packet delivery also causes hot spots in software. For example, Linux performs load balancing in software by distributing the handling of incoming packets across multiple cores; this is essential in order to sustain high packet rates. Each incoming packet is processed by the kernel on two different cores before reaching the application (which may be on a third core). In order to ensure in-order packet delivery, all of the packets for a given TCP connection must pass through

the same sequence of cores. This results in uneven core loading when two or more active connections hash to the same core; again, the hot spot persists as long as the connections are active. Measurements in [21] indicate that hot spots are the dominant cause of software-induced tail latency for TCP.

Correction (1/2023): the first paragraph of this subsection is incorrect. Out-of-order packet arrivals do not necessarily trigger packet retransmissions in TCP. Mechanisms such as triple-duplicate ACKs and RACK allow TCP to tolerate a modest degree of packet reordering without retransmissions. However, I am told by experts that asymmetries in datacenter networks can cause significant packet reorderings that exceed TCP's tolerance. In addition, performance optimizations in NICs and the Linux networking stack, such as LRO and GRO, become ineffective with even modest reorderings, resulting in significant performance degradation. Thus, both networking hardware and Linux kernel software attempt to preserve packet ordering, resulting in the problems described above.

4 TCP is beyond repair

One possible response to the problems with TCP is an incremental approach, gradually fixing the issues while maintaining application compatibility. There have already been numerous such attempts, and they have made some progress. However, this approach is unlikely to succeed: there are simply too many problems, and they are too deeply embedded in the design of TCP.

As one example, consider congestion control. This aspect of TCP has probably been studied more than any other in recent years, and a number of novel and clever techniques have been devised. One of the earliest was DCTCP [2]; it provides significant improvements in tail latency (see Figure 1) and has been widely implemented. More recent proposals such as HPCC [14] provide impressive additional improvements (they are not included in Figure 1 because they don't have Linux kernel implementations). However, all of these schemes are constrained by fundamental aspects of TCP, such as its weak congestion signal based on buffer occupancy, its inability to use switch priority queues, and its in-order delivery requirement. Significant additional improvements will be possible only by breaking some of TCP's fundamental assumptions. The Homa curve in Figure 1 shows that considerable improvement is possible (though not shown in Figure 1, Homa also delivers better tail latency than newer proposals such as HPCC).

One of the problems with an incremental approach is that TCP has many problems and they are interrelated. For example, the lack of message boundaries makes it hard to implement SRPT and limits the amount of information available for congestion control. Thus, many different parts of TCP will have to be changed before improvements will be visible.

In addition, the problems with TCP involve not just its implementation, but also its API. In order to maximize performance in the datacenter, TCP would have to switch from a model based on streams and connections to one based on mes-

sages. This is a fundamental change that will affect applications. Once applications are impacted, we might as well fix all of the other TCP problems at the same time.

The bottom line is that there are no parts of TCP worth keeping. We need a replacement protocol that is different from TCP in every significant aspect. Fortunately, such a protocol already exists: Homa [19, 21]. Homa provides an existence proof that all of TCP's problems are in fact solvable.

5 Homa

Homa represents a clean-slate redesign of network transport for the datacenter. Its design was informed by the problems with TCP as well as experience using Infiniband [23] and RDMA to implement large-scale datacenter applications. Homa's design differs from TCP in every one of the dimensions discussed in Section 3. This section summarizes Homa's features briefly; for details, see [19] and [21].

5.1 Messages

Homa is message-based. More precisely, it implements remote procedure calls (RPCs), where a client sends a request message to a server and eventually receives a response message. The primary advantage of messages is that they expose dispatchable units to the transport layer. This enables more efficient load balancing: multiple threads can safely read from a single socket, and a NIC-based implementation of the protocol could dispatch messages directly to a pool of worker threads via kernel bypass. Having explicit message boundaries also enables run-to-completion scheduling in the transport, such as SRPT, and provides a more powerful congestion signal (see below).

Messages have one disadvantage relative to streams: it is difficult to pipeline the implementation of a single large message. For example, an application cannot receive any part of a message until the entire message has been received. Thus a single large message will have higher latency than the same data sent via a stream. However, large data transfers can be handled by sending multiple messages in parallel, which permits pipelining between messages.

5.2 No connections

Homa is connectionless. There is no connection setup overhead, and an application can use a single socket to manage any number of concurrent RPCs with any number of peers. Each RPC is handled independently: there are no ordering guarantees between concurrent RPCs.

The state maintained by Homa falls into three major categories:

- Sockets: Homa's state per socket is roughly equivalent to that for TCP, but Homa applications can get by with a single socket, whereas TCP applications require one socket per peer.
- RPCs: Homa keeps about 300 bytes of state for each active RPC. This state is discarded once the RPC has completed, so the total amount of state is proportional to the number of active RPCs, not the total number of peers.

 Peers: each Homa host keeps about 200 bytes of state for each other host, most of which is IP-level routing information. This is much smaller than the 2000 bytes of state that TCP maintains per connection.

In spite of its lack of connections, Homa ensures end-toend reliability for RPCs (or reports errors after unrecoverable network or host failures). There is no need for applications to maintain additional timeouts. Mechanisms such as flow control, retry, and congestion control are implemented using per-RPC state; one way of thinking about Homa is that it implements a short-lived and lightweight connection for each RPC.

5.3 SRPT

Homa implements an SRPT scheduling policy in order to favor shorter messages. It uses several techniques for this, of which the most notable is that it takes advantage of the priority queues provided by modern switches. This allows higher-priority (shorter) messages to bypass packets queued for lower-priority (longer) messages. As can be seen in Figure 1 this results in considerable improvements in tail latency compared to either TCP or DCTCP. Messages of all lengths benefit from SRPT: even the longest messages have significantly lower latency under Homa than under TCP or DCTCP.

One potential concern about SRPT is that the longest messages might suffer disproportionately high tail latencies or even starve. This problem has not yet been observed in practice and is difficult to produce even with an adversarial approach. Nonetheless, the Linux implementation of Homa contains an additional safeguard: a small fraction of each host's bandwidth (typically 5–10%) is dedicated to the *oldest* message rather than the smallest. This eliminates starvation and improves tail latency for long messages in pathological cases, while still using run-to-completion.

Homa's use of priority queues eliminates the "pick your poison" tradeoff between latency and bandwidth discussed in Section 3.4. Homa intentionally allows some buffers from longer messages to accumulate in low-priority queues (*over-commitment*); these ensure high link utilization. Short messages still achieve low latency since they use higher priority queues.

5.4 Receiver-driven congestion control

Homa manages congestion from the receiver, not the sender. This makes sense because the primary location for congestion is the receiver's downlink (Homa eliminates core congestion as discussed in Section 5.5 below). The receiver has knowledge of all its incoming messages, so it is in a better position to manage this congestion. When a sender transmits a message, it can send a few *unscheduled packets* unilaterally (enough to cover the round-trip time), but the remaining *scheduled packets* may only be sent in response to *grants* from the receiver. With this mechanism, the receiver can limit congestion at its downlink, and it also uses the grants to prioritize shorter messages.

Messages provide a powerful congestion signal that is not available in stream-based protocols. Although message arrival

is unpredictable, once the first packet of the message has been seen, the total length of the message is known. This enables proactive approaches to congestion control, such as throttling other messages during this message's lifetime and ramping them up again when this message completes. In contrast, TCP can only be reactive, based on buffer occupancy.

Incast can occur if many senders simultaneously send unscheduled packets, but Homa's RPC orientation enables a simple mitigation; see the Homa papers for details.

5.5 Out-of-order packets

A key design feature of Homa is that it can tolerate out-oforder packet arrivals. This provides considerably more flexibility for load balancing. For example, packet-level spraying can be used to distribute packets across the network fabric instead of flow-consistent routing as in TCP. If Homa becomes widely deployed, I hypothesize that core congestion will cease to exist as a significant networking problem, as long as the core is not systemically overloaded. Homa's tolerance for outof-order arrivals also allows more flexibility for load balancing in software.

5.6 Related work

Several recent papers have claimed to identify problems with Homa and/or to improve upon its performance, including Aeolus [7], PowerTCP [1], and DcPIM [4]. However, all of these papers have significant flaws, such as not implementing Homa correctly or measuring it under artificial restrictions (e.g. Aeolus uses statically buffer allocation in switches). For a more detailed discussion of these papers, see the Homa Wiki [8]. The Homa Wiki also contains a variety of other information about Homa, and will be updated in the future to include new information and related work.

6 What about Infiniband?

There are other TCP alternatives besides Homa, but none that appear to meet the needs of datacenter computing. One of the best known alternatives is Infiniband [23], which has been widely adopted in the high-performance computing (HPC) arena, and has recently seen increasing use in datacenters via RoCE, which layers the RDMA API over Ethernet.

The primary advantage of RDMA is that it provides very low latency on unloaded networks. It achieves this by offloading the transport protocol implementation to the NIC and allowing user processes to bypass the kernel and communicate directly with the NIC. Infiniband/RDMA NICs have a well-deserved reputation for very high performance.

However, RDMA shares most of TCP's problems. It is based on streams and connections (RDMA also offers unreliable datagrams, but these have problems similar to those for UDP). It requires in-order packet delivery. Its congestion control mechanism, based on priority flow control (PFC), is different from TCP's, but it is also problematic. And, it does not implement an SRPT priority mechanism.

RDMA has the additional disadvantage that the NIC-based protocol implementations are proprietary, so it is difficult to

find out exactly how they behave and to track down problems. As one example, the RAMCloud project found several performance anomalies with Infiniband, especially at high load; in most cases it was not possible to track them down because of the closed nature of the implementation.

Future transport implementations should adopt Infiniband's kernel bypass approach, but it seems unlikely that Infiniband itself can solve all of TCP's problems.

7 Getting there from here

It is hard to imagine a computing standard more entrenched than TCP, so replacing it will be difficult. To make matters worse, Homa (or any protocol that fixes all of TCP's problems) requires API changes, meaning that application code will have to be modified. Given the enormous number of applications that code directly to the sockets interface, the task of modifying them all seems insurmountable, at least for the near future.

Fortunately, it is not necessary to replace TCP for all applications. The applications with the greatest need for a new transport protocol are newer large-scale datacenter applications. Most of these applications do not code to the sockets API; instead, they are layered above one of a relatively small number of RPC frameworks such as gRPC [6] or Apache Thrift [24]. The easiest way to bring a new protocol into widespread use is to integrate it with the major RPC frameworks. This is a fairly manageable task, and once it is done, applications using the frameworks can switch to Homa with little or no work.

Work on framework integration has already begun: a gRPC driver for Homa now exists for C++ applications, and Java support is underway. This work is based on the Linux kernel implementation of Homa [21].

8 Conclusion

TCP is the wrong protocol for datacenter computing. Every aspect of TCP's design is wrong: there is no part worth keeping. If we want to eliminate the "datacenter tax", we must find a way to move most datacenter traffic to a radically different protocol. Homa offers an alternative that appears to solve all of TCP's problems. The best way to bring Homa into widespread usage is integrate it with the RPC frameworks that underly most large-scale datacenter applications.

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